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The Old Friary, Friars Lane, Beverley, East Riding of Yorkshire Tree-ring analysis of oak timbers

Alison Arnold, Robert Howard and Cathy Tyers

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THE OLD FRIARY
FRIARS LANE
BEVERLEY
EAST RIDING YORKSHIRE

Tree-ring analysis of oak timbers

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SUMMARY
Tree-ring analysis of samples taken from oak timbers of various structures within The Old Friary, Beverley resulted in the construction and dating of a single site sequence. This site sequence contains five samples from timbers of the Common Room roof, all reused, and spans the period AD 1050–1220. Interpretation of the surviving sapwood suggests felling of these timbers occurred in AD 1226–51.

CONTRIBUTORS
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We would like to thank David Cook of the Yorkshire Vernacular Buildings Study Group for facilitating access and staff at the Friary for their patience and assistance during the assessment and sampling. The building description and drawings used to illustrate this report are taken from a survey of the building by the Yorkshire Vernacular Buildings Study Group with additional plans produced by Ingleby and Hobson Architects. Thanks are also given to Shahina Farid of the Historic England Scientific Dating Team for her advice and assistance throughout the production of this report and to Rebecca Lane of the Historic England Architectural Investigation Team who coordinated this project.

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CONTENTS

INTRODUCTION

The *Early Fabric in Historic Towns: Voluntary Group Projects*, funded by Historic England, have been developed in the recognition and acknowledgement of the excellent work being undertaken by local vernacular groups in the study of local architectural trends and fabrics. The project's intention is to encourage this type of study through the provision of support and to facilitate training of more people in building analysis and recording. The local projects were coordinated by Rebecca Lane (Historic England South West Region: Senior Architectural Investigation).

Early Fabric in Beverley Project

Whilst there is a corpus of research on form and age of the town of Beverley, it does not cover detailed examination of early fabric or aspects of typology, with analysis and interpretation of existing buildings until now not having benefited from dendrochronology, with the exception of some limited work on the Minster.

Initially, 13 properties were identified that were thought to be key to understanding the town's architectural development for a programme of comprehensive investigation. These properties were assessed for their suitability for tree-ring dating and those found to contain timbers potentially suitable for analysis were sampled. As the project progressed and some of the original buildings identified were rejected as unsuitable for tree-ring dating, further candidates for tree-ring analysis were assessed and sampled if appropriate.

It was hoped that successful dating of these buildings would extend the knowledge of early fabric and selected buildings in the historic town of Beverley in support of Historic England's responsibility to identify and understand the urban vernacular and historic environment of a market town. The reports produced on the buildings recorded as part of this project by the Yorkshire Vernacular Buildings Study Group, led by David Cook, will be held in the YVBSG archive and will be available through their website (www.yvbsg.org.uk), whilst a summary of the project is presented in Vernacular Architecture (Cook and Neave 2018).

THE OLD FRIARY

The Old Friary (List Entry Number 1084062), thought to have been a guest house, library or infirmary, is located on the north-west side of Friars Lane in Beverley (Figs 1–3) and is the only surviving building of the Dominican Friary complex. It is a two-storey linear building, aligned north-east/south-west (east/west for the benefit of this report) with a south-west wing and a two-storey porch (Fig 4).

Although the building is thought to date from the fourteenth century, as evidenced by surviving footings and a doorway, a substantial fire in AD 1449 necessitated the rebuilding of large portions of it, including (and below) the Common Room and the Female Dormitory. The west end, containing the Great Hall, is thought to date to the sixteenth century, as is the south-west wing and porch. Further alterations were undertaken during the seventeenth, eighteenth, and nineteenth centuries with the eastern end built in AD 1984–5.

Great Hall

This first-floor hall, open to the roof, consists of three bays and is situated at the western end of the range. The roof over this has three truncated principal rafter trusses and a false hammerbeam truss (Truss 3). The principal rafter trusses have two sets of threaded purlins (Fig 5). Either side of this truss is a reused cross beam, both cross beams are likely to be later insertions incorporated to support a joisted floor above (since removed).

Common Room

Adjacent to the Great Hall and separated from it by a stud and beam partition is the Common Room; this is again open to the roof. The roof over this area is of common rafter type and utilises a substantial amount of reused timber. It has very high collars and one remaining soulace, cross-beams and a single row of purlins to each slope that run along the back of the rafters, although not along the entire length of the roof (Fig 6).

Female Dormitory

Further east and down a step is the Female Dormitory, also open to the roof and about the same length as the Common Room. This roof is again of common rafter and collar type, with the rafters sitting on the wall tops. Not every rafter frame has a collar, these being distributed about one to every third rafter frame. There is a single row of purlins to each slope, clasped between the collars and the rafters. There are three, irregularly spaced reused cross beams set into the brick walls, just below the tops (Fig 7).

SAMPLING

A total of 41 samples were taken from various oak (*Quercus* sp.) timbers at both roof and ground floor level. Each core sample was given the code BEV-D and numbered 01–41. The location of all samples was noted at the time of sampling and has been marked on Figures 4 and 8–13. Further details relating to the samples can be found in Table 1. Trusses and beams have been numbered from east to west.

ANALYSIS AND RESULTS

Eleven samples, five from the truncated rafter roof over the Great Hall and landing, four from the ground-floor timbers, and two from the common-rafter roof over the Female Dormitory, had too few rings for secure dating and so were rejected prior to measurement. The remaining 30 samples were prepared by sanding and polishing and their growth-ring width measured; the data of these measurements are given at the end of the report. These samples were then compared with each other by the Litton/Zainodin grouping programme (see Appendix).

Five samples matched each other at a minimum *t*-value of 5.5 and were combined at the relevant offset positions to form BEVDSQ01, a site sequence of 171 rings (Fig 14). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to match securely and consistently as a first-ring date of AD 1050 and a last-measured ring date of AD 1220. The evidence for this dating is given in Table 2.

Some tenuous, but unproven, matching was noted between some of the individual samples. Attempts were then made to date the ungrouped samples by comparing them individually against the reference chronologies but no secure matches were noted and all remain undated.

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of samples from four common rafters and a collar from the common rafter roof over the Common Room. In the absence of sapwood complete to the bark edge, felling date ranges or *terminus post quem* dates for felling have been calculated using the estimate that 95% of mature trees in this region have 15–40 sapwood rings. Four of these samples have the heartwood/sapwood boundary ring, which in all cases is broadly contemporary, ranging from AD 1202 (BEV-D13) to AD 1218 (BEV-D14), and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1211, allowing an estimated felling date to be calculated for the five timbers represented of AD 1226–51. The final dated sample, BEV-D12, does not have the heartwood/sapwood boundary ring, but with a last-measured ring date of AD 1197 this has a *terminus post quem* for felling of AD 1212, not incompatible with this timber also having been felled in AD 1226–51.

DISCUSSION

Four of the reused common rafters and one of the reused collars contained within the roof over the Common Room have been successfully dated, with all five timbers thought to have been felled in the period AD 1226–51. With these five timbers all being reused this dating does not signify when the extant roof was constructed, except to say that it would have been after this date.

With the Old Friary itself thought to have been founded in AD 1240, a date which falls within the felling date range obtained, it is tempting to suggest that these beams were salvaged from one of the original Friary buildings, perhaps following its damage/destruction in the AD 1449 fire. However, this is supposition and cannot be proven by the dendrochronology.

Two of the dated samples, BEV-D14 and BEV-D17, both taken from common rafters, match each other at a value of $t = 10.3$. This is a high enough level to make it possible that both timbers were cut from the same tree.

It is disappointing that out of the 30 suitable samples it has only been possible to date five of them. In part, this may be due to the high number of reused timbers sampled, potentially representing multiple building phases. However, the success rate for the dating of apparently suitable samples by dendrochronology in Beverley and its environs is markedly below the national average. Whether this is to do with the area having a localised micro-climate or other environmental factors is unclear at present but it is to be hoped that with this project and other local research being undertaken this situation will be better understood and improved in the future by establishing a strong local network of reference chronologies.

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TABLES

Table 1: Details of tree-ring samples taken from The Old Friary, Beverley, East Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Truncated rafter roof (Great Hall & landing)						
BEV-D01	Beam 2	127	25C	----	----	----
BEV-D02	South principal rafter, truss 3	61	h/s	----	----	----
BEV-D03	South archbrace, truss 3	64	h/s	----	----	----
BEV-D04	Beam 1	125	18C	----	----	----
BEV-D05	North principal rafter, truss 3	NM	--	----	----	----
BEV-D06	North purlin, truss 2-3	NM	--	----	----	----
BEV-D07	North archbrace, truss 3	NM	--	----	----	----
BEV-D08	South principal rafter, truss 1	50	h/s	----	----	----
BEV-D09	South inner rafter, truss 1	NM	--	----	----	----
BEV-D10	North principal rafter, truss 1	NM	--	----	----	----
BEV-D11	Tiebeam, truss 2	54	h/s	----	----	----
Common rafter roof (Common Room)						
BEV-D12	South common rafter 3 - reused	148	--	1050	----	1197
BEV-D13	South common rafter 4 – reused	132	h/s	1071	1202	1202
BEV-D14	North common rafter 10 – reused	102	02	1119	1218	1220
BEV-D15	North common rafter 12 -reused	109	--	----	----	----
BEV-D16	Collar 12 – reused	78	02	1133	1208	1210
BEV-D17	South common rafter 16 - reused	108	h/s	1107	1214	1214
BEV-D18	Tiebeam	154	06	----	----	----
BEV-D19	East beam	136	h/s	----	----	----
BEV-D20	Floor/stair beam	141	h/s	----	---	----
Ground-floor timbers						
BEV-D21	North post	66	h/s	----	----	----
BEV-D22	South post	63	h/s	----	----	----
BEV-D23	Horizontal beam	86	h/s	---	----	----
BEV-D24	North brace	75	h/s	----	----	----

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
BEV-D25	South brace	102	h/s	----	----	----
BEV-D26	Ceiling beam – kitchen	83	--	----	----	----
BEV-D27	Ceiling beam – exhibition partition	NM	--	----	----	----
BEV-D28	Ceiling beam – exhibition	50	h/s	----	----	----
BEV-D29	South post	52	--	----	----	----
BEV-D30	Ceiling beam – north	58	17C	----	---	----
BEV-D31	Ceiling beam	NM	--	----	----	----
BEV-D32	Joist 3	NM	--	----	----	----
BEV-D33	Joist 4	NM	--	----	---	----
Common rafter roof (Female Dormitory)						
BEV-D34	Beam 1 – reused	85	h/s	----	----	----
BEV-D35	Beam 2 – reused	67	09	----	----	----
BEV-D36	Beam 3 – reused	121	h/s	----	---	----
BEV-D37	North common rafter 7 – reused	NM	--	----	----	----
BEV-D38	North common rafter 8 – reused	NM	--	----	----	----
BEV-D39	Lintel (inner) N3	79	--	----	----	----
BEV-D40	Lintel (mid) N3	72	--	----	----	----
BEV-D41	Cill	107	--	----	----	----

NM = not measured
h/s = heartwood/sapwood boundary is the last-measured ring
C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence BEVDSQ01 and the reference chronologies when the first-ring date is AD 1050 and the last-measured ring date is AD 1220

Reference chronology	*t*-value	Span of chronology	Reference
Angel Choir, Lincoln Cathedral, Lincolnshire	10.0	AD 904–1257	Laxton and Litton 1988
Woodford Old Hall, Stockport, Greater Manchester	9.9	AD 1035–1299	Arnold and Howard 2018 unpubl
Peterborough Cathedral, Cambridgeshire	8.7	AD 921–1194	Tyers 2004
Second Wood Street, Nantwich, Cheshire	8.7	AD 932–1509	Tyers 2005
All Hallow's Church, Kirkburton, West Yorkshire	8.4	AD 999–1218	Arnold and Howard 2007a
Gloucester Blackfriars, Gloucester, Gloucestershire	8.3	AD 1024–1237	Howard *et al* 2002
Eastgate, Beverley, East Yorkshire	8.1	AD 858–1310	Groves 1992
Naas House, Lydney, Gloucestershire	8.1	AD 1127–1229	Howard *et al* 1998
186/7 Horninglow St, Burton upon Trent, Staffordshire	8.0	AD 1101–1345	Howard *et al* 1995
St Mary's Grove / Eastgate Street, Stafford, Staffordshire	7.9	AD 884–1189	Groves 1987a; Groves 1987b
St Hughs' Choir, Lincoln Cathedral, Lincolnshire	7.7	AD 882–1184	Laxton *et al* 1984
Kenilworth Castle Gatehouse, Kenilworth, Warwickshire	7.5	AD 1092–1332	Arnold and Howard 2007b
St Mary's Church, Stockport, Greater Manchester	7.5	AD 1099–1293	Arnold and Howard 2011

FIGURES

Figure 1: Map to show the general location of Beverley (red ellipse).

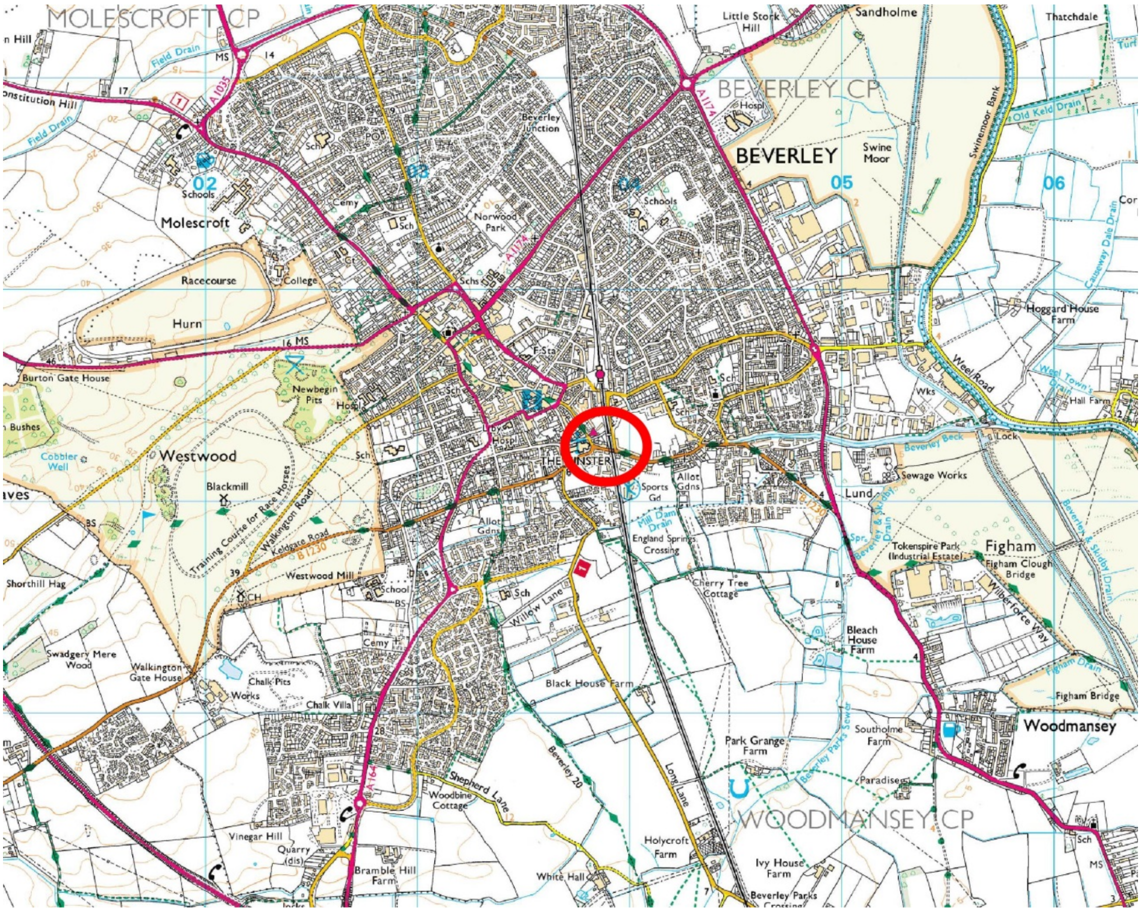

Figure 2: Map to show the general location of The Old Friary in Beverley (red ellipse), arrowed. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900

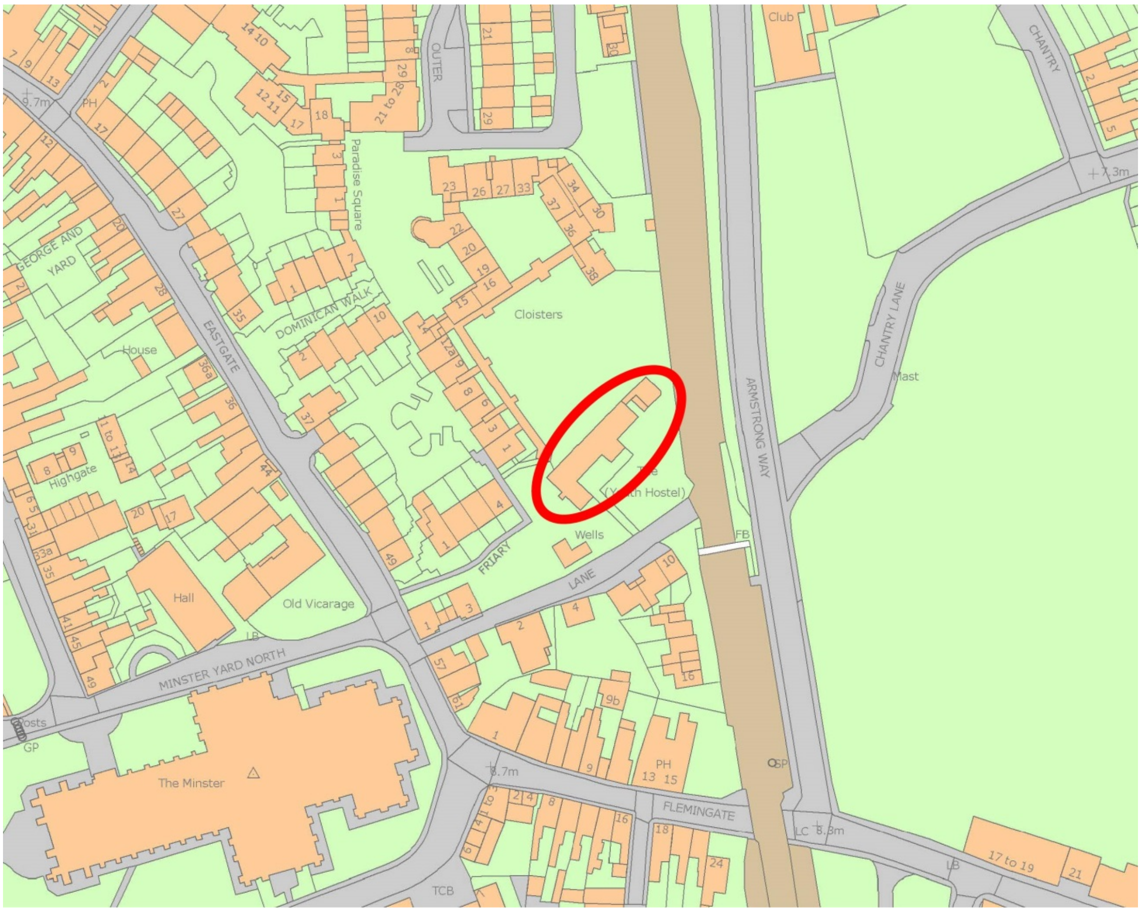

Figure 3: Map to show the location of The Old Friary in Beverley (red ellipse).

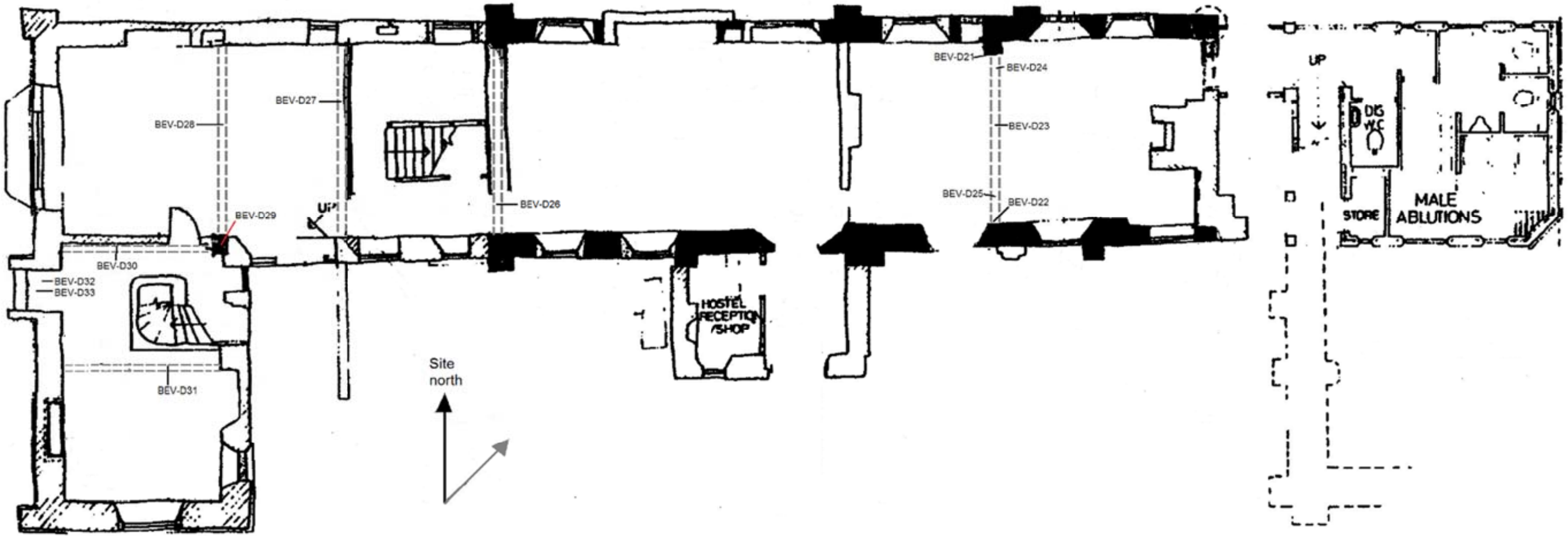

Figure 4: Plan Ground-floor plan, showing the location of samples BEV-D21–33 (after Ingleby and Hobson Architects)

Figure 5: Great Hall, roof with beam 1 in foreground, photograph taken from the east (Robert Howard)

Figure 6: Common Room roof, photograph taken from the west (Robert Howard)

Figure 7: Female Dormitory roof, photograph taken from the west (Robert Howard)

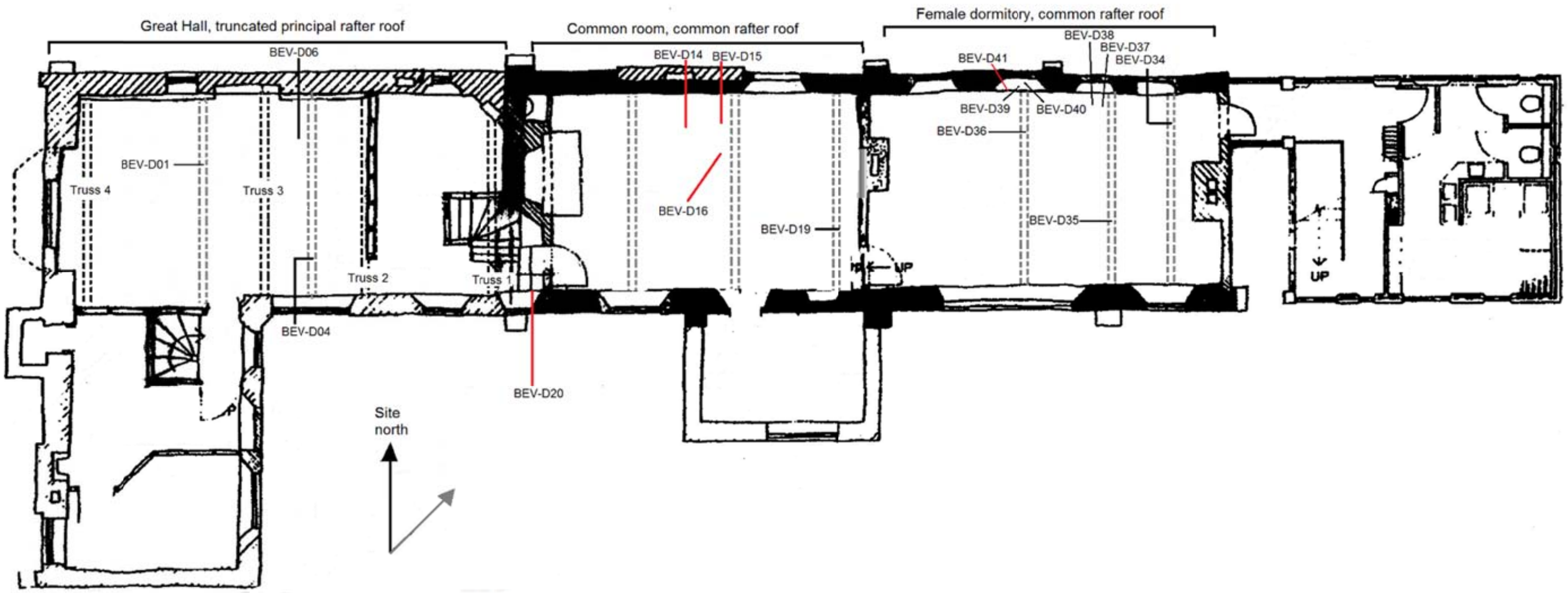

Figure 8: First-floor plan, showing the location of samples BEV-D01, BEV-D04, BEV-D06, BEV-D14–16, BEV-D19–20, and BEV-D34–41 (after Ingleby & Hobson Architects)

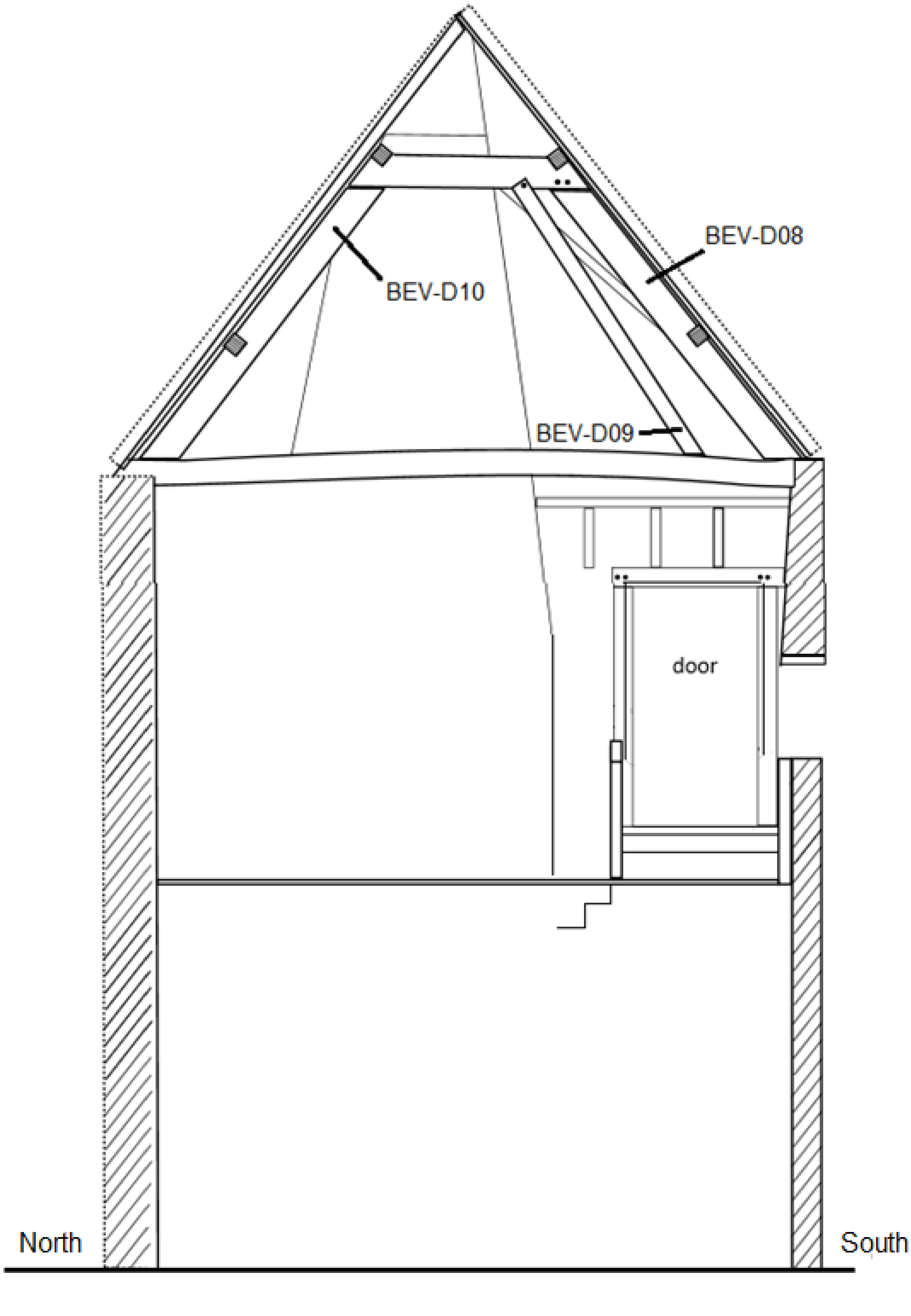

Figure 9: Great Hall, truss 1, showing the location of sample BEV-D08–10 (after YVBSG 2015)

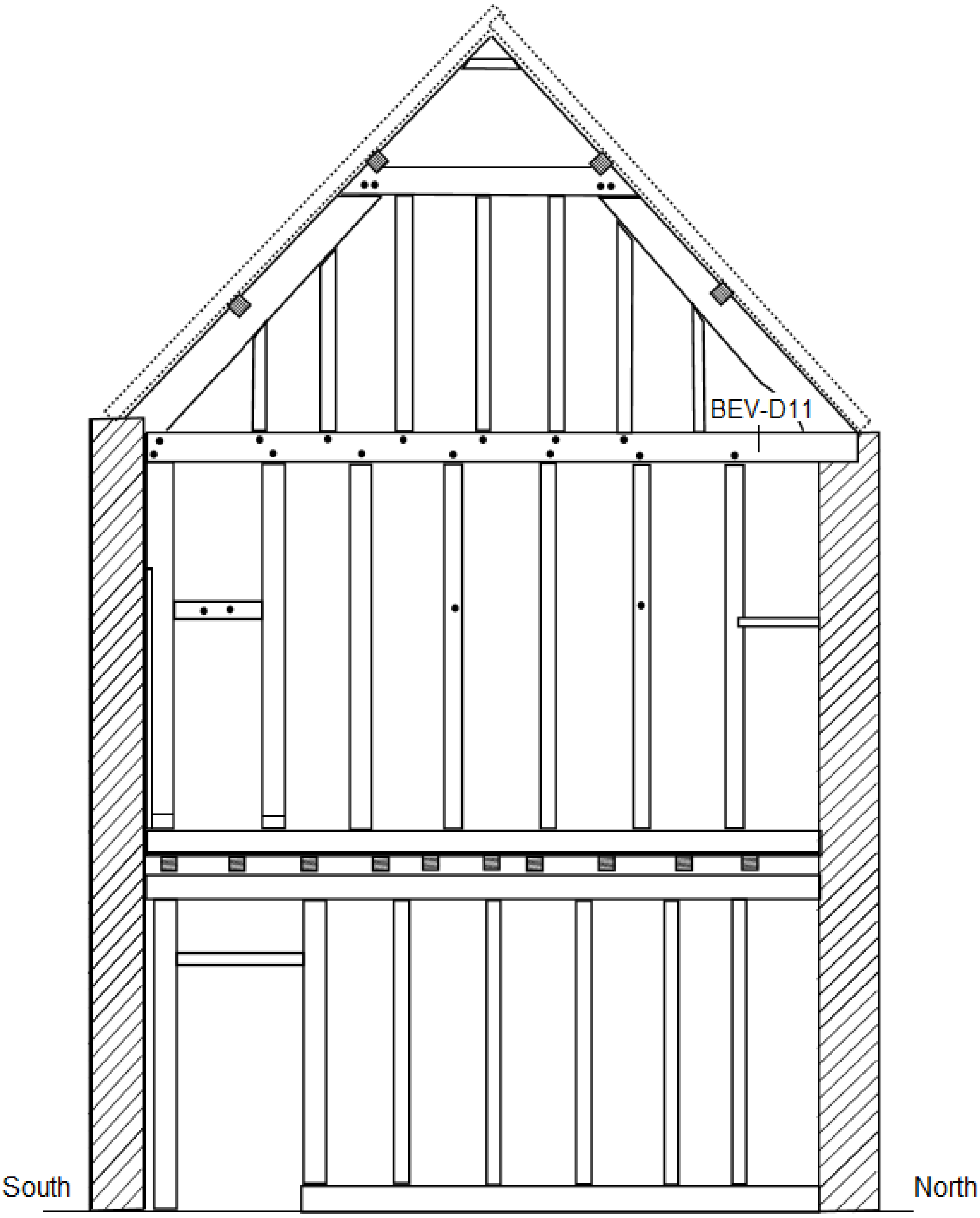

Figure 10: Great Hall, truss 2, showing the location of sample BEV-D11 (after YVBSG 2015)

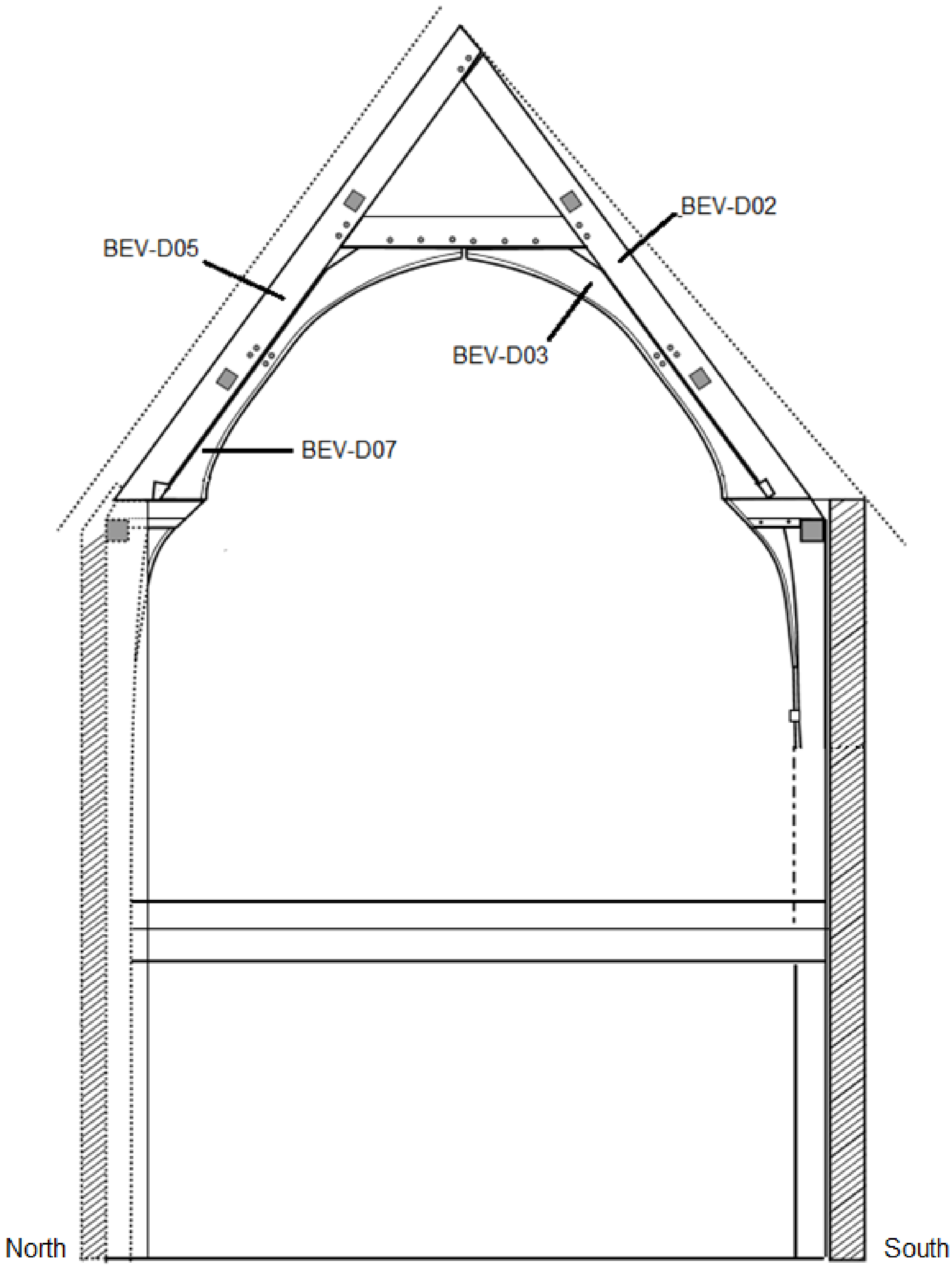

Figure 11: Great Hall, truss 3, showing the location of samples BEV-D02–03, BEV-D05, and BEV-D07 (after YVBSG 2015)

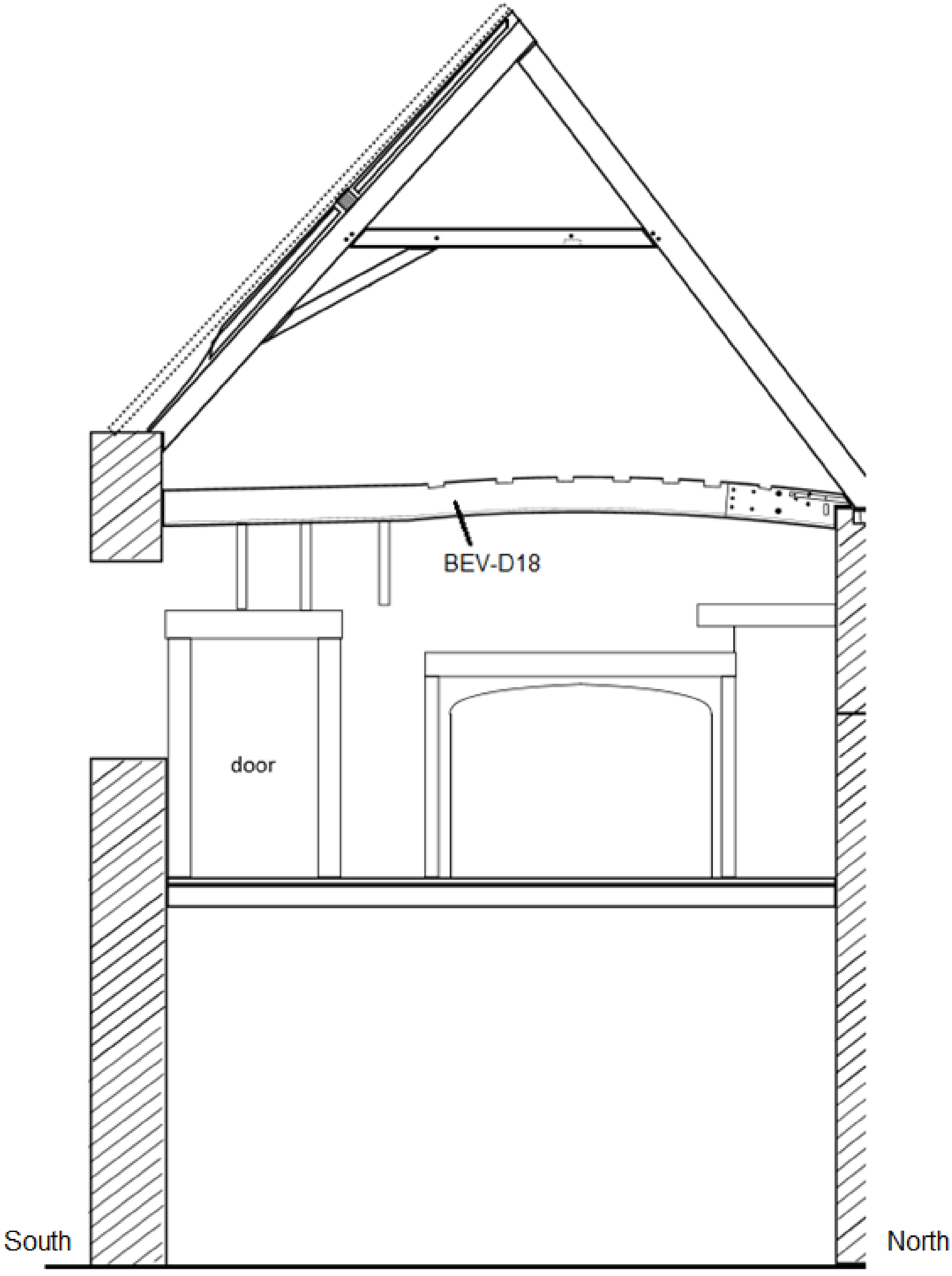

Figure 12: Common room, truss, showing the location of sample BEV-D18 (after YVBSG 2015)

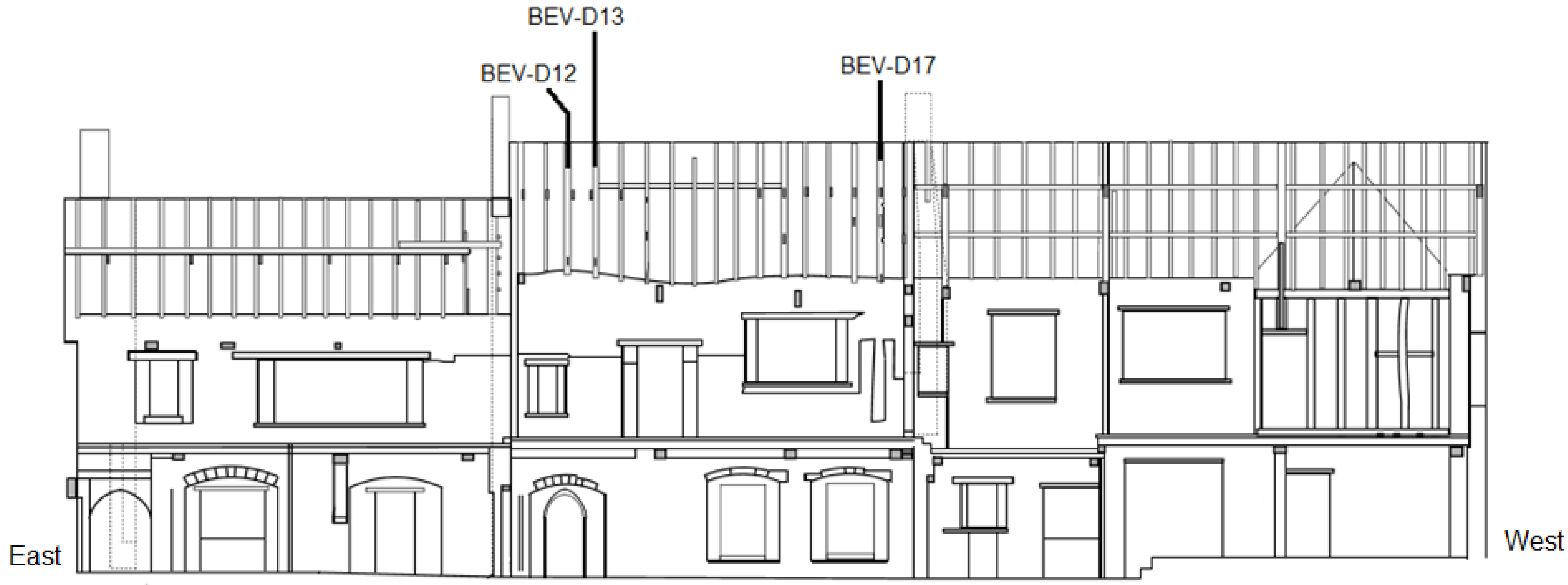

Figure 13: Southern elevation (looking south), showing the location of samples BEV-D12–13 and BEV-D17 (after YVBSG 2015)

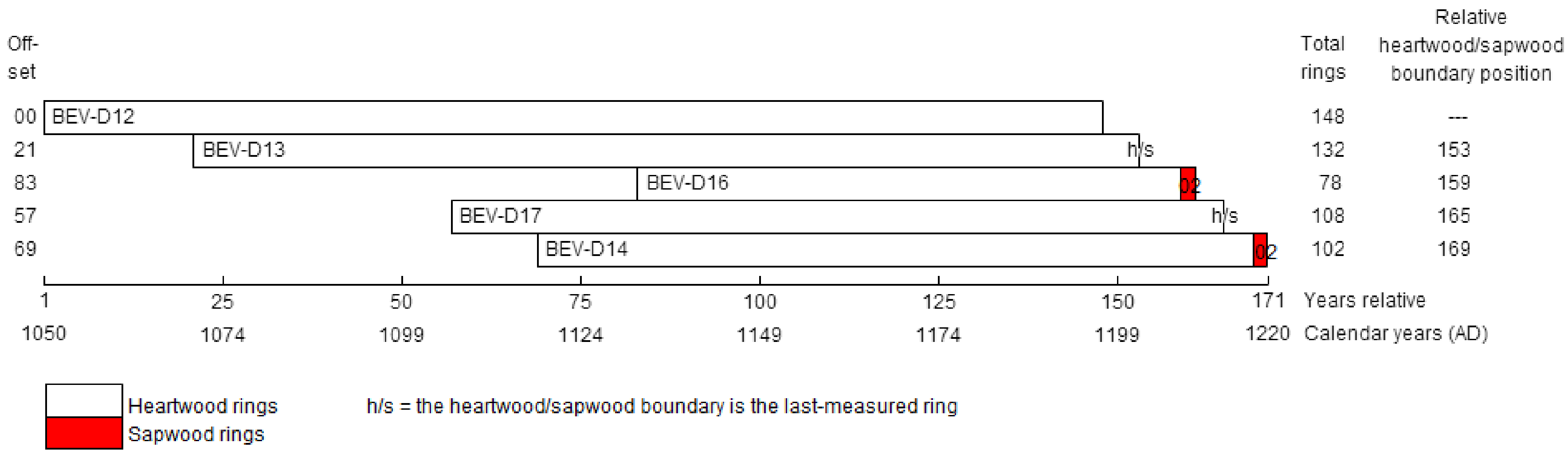

Figure 14: Bar diagram to show the position of samples in site sequence BEVDSQ01

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BEV-D01A 127
175 167 164 162 200 224 232 160 178 135 144 137 212 231 191 277 246 237 112 89
97 123 89 87 107 105 115 79 134 155 133 140 117 129 84 83 82 73 60 65
66 72 96 92 74 61 50 69 59 53 59 67 77 80 72 83 42 21 29 46
33 32 29 28 25 32 42 42 43 35 45 40 34 44 66 95 105 86 88 90
115 77 62 76 84 91 99 85 128 143 115 130 165 169 116 85 88 81 128 104
125 111 61 94 112 95 95 85 129 109 91 124 137 125 92 128 141 172 148 109
119 136 139 129 163 149 122

BEV-D01B 127
162 163 161 169 192 228 245 140 165 121 143 149 202 226 210 237 233 239 108 91
101 121 96 77 122 107 114 93 130 174 150 137 117 129 105 76 88 69 76 56
64 84 103 100 76 59 53 67 58 52 65 79 74 80 77 81 43 21 34 43
29 33 27 28 34 31 30 49 39 38 45 38 40 42 64 93 100 81 97 86
115 69 70 79 76 100 93 92 116 128 124 125 174 160 117 87 92 80 131 103
129 113 66 94 115 89 109 84 123 113 92 113 142 116 102 129 142 150 117 108
122 148 134 115 159 142 128

BEV-D02A 61
212 297 349 298 298 370 404 383 526 441 368 318 255 231 229 204 171 156 167 158
165 125 93 80 91 125 130 166 230 201 188 203 192 217 217 209 117 132 146 176
111 122 152 192 170 245 208 238 211 209 186 205 235 190 127 144 157 149 159 131
150

BEV-D02B 61
204 298 350 298 289 374 408 382 541 450 368 295 292 224 276 153 167 162 166 158
174 120 98 77 107 127 136 196 236 197 202 195 191 209 233 204 127 126 162 165
114 118 163 183 183 249 206 240 210 219 182 205 234 205 137 137 166 137 161 127
146

BEV-D03A 64
298 351 441 476 465 302 253 271 360 472 355 399 382 386 315 400 441 378 406 462
404 399 365 359 341 341 194 171 173 123 118 120 110 132 157 199 219 212 181 195
208 191 165 143 135 156 137 232 188 158 217 193 199 239 115 153 123 142 178 182
186 160 242 147

BEV-D03B 64
313 358 443 494 450 332 291 298 386 486 372 409 403 416 392 407 462 360 386 424
347 374 302 349 353 356 212 181 179 133 130 139 114 159 161 190 198 203 179 181
219 184 152 135 124 157 122 211 176 149 218 209 185 268 143 154 134 153 229 179
186 155 232 156

BEV-D04A 125
201 153 164 130 147 106 105 88 121 137 234 200 195 203 144 149 145 127 109 128
79 69 188 167 145 89 187 163 108 70 67 90 97 83 120 116 117 108 112 130
180 163 115 77 65 100 127 61 86 140 118 139 155 137 69 105 115 134 79 137
143 67 98 90 123 145 121 113 98 119 117 116 153 149 152 113 129 99 119 145

106 153 123 116 130 128 137 144 106 132 135 96 134 76 84 60 109 65 92 98
60 79 63 73 76 71 94 77 67 66 70 100 59 104 112 89 81 94 67 67
49 67 64 60 63

BEV-D04B 125
180 157 167 130 151 103 105 84 123 134 243 183 163 182 168 153 147 144 116 112
79 69 192 166 150 91 194 153 108 74 65 82 99 87 122 117 120 108 117 143
178 164 118 78 62 100 120 69 65 107 110 140 158 127 79 110 119 142 74 137
147 63 98 90 120 159 125 101 109 125 118 121 152 149 149 122 124 101 121 139
108 160 131 109 135 129 136 115 130 143 137 90 132 76 85 64 108 70 93 101
60 81 63 70 76 70 94 85 66 68 71 87 65 110 105 86 75 96 66 69
45 65 67 66 57

BEV-D08A 50
227 227 341 314 298 262 228 210 276 185 175 157 245 275 349 401 334 288 198 242
277 252 180 159 140 151 139 191 160 120 190 272 287 286 223 256 244 247 172 250
237 268 172 156 302 275 293 164 261 209

BEV-D08B 50
225 224 341 307 298 253 240 211 272 149 181 154 248 266 352 396 358 273 189 266
251 275 178 168 139 139 135 195 154 129 186 260 271 276 231 256 258 209 178 256
241 279 154 159 290 295 289 171 275 198

BEV-D11A 54
310 366 543 329 456 409 389 320 136 207 152 192 195 173 201 209 255 257 170 402
413 360 504 362 132 140 193 159 202 166 126 89 100 113 177 121 77 93 130 167
186 293 200 180 149 139 168 188 228 119 139 220 188 178

BEV-D11B 54
289 351 524 315 444 407 402 318 132 225 136 182 168 182 207 206 240 250 169 404
422 349 477 363 127 140 182 162 203 165 135 71 112 104 173 131 82 87 131 169
187 259 190 182 142 145 152 181 243 114 142 199 193 174

BEV-D12A 148
206 179 190 145 181 204 235 230 208 223 186 155 164 157 140 145 180 161 136 128
140 115 93 101 86 136 112 114 117 100 120 124 108 125 113 126 122 117 152 147
93 111 146 93 88 91 77 61 94 101 87 74 80 100 71 70 90 94 116 106
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82 87 82 87 84 70 66 55 78 70 81 86 77 66 75 62 67 60 64 60
56 63 57 56 40 47 50 40 48 61 58 52 52 60 51 53 65 65 49 60
61 71 62 58 48 69 61 58 65 83 50 53 67 76 52 59 61 81 63 74
79 74 71 73 77 76 81 79

BEV-D12B 148
213 177 197 147 174 206 218 225 208 211 193 159 170 161 148 144 174 161 134 134
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98 108 149 93 82 94 85 68 91 100 87 73 83 100 78 73 82 87 112 106
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59 62 58 53 38 53 49 41 41 63 62 50 48 61 65 41 68 59 43 57
64 78 61 62 53 63 69 57 57 67 56 59 64 76 51 65 72 71 51 81
84 76 66 74 79 70 86 86

BEV-D13A 132
99 114 115 121 143 122 111 141 121 191 149 169 171 130 127 117 128 132 132 102
131 164 94 93 98 93 64 88 107 92 86 117 114 90 90 111 101 165 135 107
82 117 107 120 121 134 144 124 94 111 124 138 152 114 109 121 146 120 106 100
111 117 106 123 81 86 72 92 89 89 105 95 85 88 74 87 78 73 88 82
79 68 70 81 82 64 67 68 82 90 90 90 75 66 65 71 65 75 70 76
65 75 76 79 77 84 76 62 72 70 80 80 78 66 69 70 87 73 64 85
66 70 85 83 93 104 83 71 82 75 98 78

BEV-D13B 132
107 132 115 125 145 122 105 142 124 189 152 163 163 117 126 114 116 140 137 108
130 162 97 98 92 93 70 99 94 100 94 104 114 85 85 112 103 154 134 95
81 110 101 123 118 121 149 118 96 101 120 139 151 116 105 122 147 119 112 95
105 110 102 122 89 86 75 88 89 83 108 90 89 72 86 80 93 65 88 82
72 77 73 79 72 85 71 67 87 86 95 92 72 66 71 60 70 72 73 81
67 72 74 81 78 72 72 73 77 61 80 76 87 65 65 70 93 66 70 76
72 60 93 84 96 108 75 75 88 79 88 85

BEV-D14A 102
177 125 161 226 241 188 201 169 214 210 152 192 220 169 146 184 180 158 136 187
145 234 240 178 172 184 167 148 137 121 158 120 170 142 198 197 190 188 140 104
229 213 166 122 135 145 144 117 93 100 155 132 124 120 92 88 90 96 80 88
98 97 83 114 93 80 72 70 76 58 67 65 63 95 110 86 93 135 116 87
96 76 102 96 93 97 90 73 80 95 110 102 93 69 67 68 79 78 82 92
70 82

BEV-D14B 102
173 129 162 225 248 183 201 167 204 211 157 202 213 165 145 195 183 148 131 190
147 238 254 180 174 178 161 144 133 134 144 135 159 144 199 193 177 203 141 96
227 210 163 128 135 138 148 114 96 101 154 128 121 123 96 80 93 93 81 92
97 93 84 110 99 77 71 72 75 61 58 72 63 92 112 83 97 134 113 88
93 81 99 99 95 95 91 71 80 91 112 100 97 67 68 66 80 77 84 87
70 85

BEV-D15A 109
284 201 156 261 312 326 397 345 337 303 285 199 311 262 280 194 221 217 182 179
311 327 277 194 187 155 208 112 103 119 169 183 162 91 92 100 91 118 116 65
79 95 59 48 69 81 135 110 60 128 104 56 61 43 39 66 66 40 73 57
45 40 69 56 88 63 54 59 42 30 40 42 79 79 85 83 82 57 106 76
75 166 141 149 139 67 62 71 105 64 104 103 114 56 64 63 48 72 126 90
77 77 88 62 46 40 63 75 50

BEV-D15B 109
287 197 156 251 331 345 388 324 338 300 276 201 308 264 285 184 214 220 174 187
308 326 274 181 198 160 209 110 103 120 172 179 157 101 90 98 90 115 114 67
81 93 52 57 69 80 133 114 54 129 112 48 53 48 37 61 68 40 63 62
48 35 65 59 88 67 57 56 41 26 40 46 80 78 82 82 83 59 109 73
77 165 153 136 141 60 62 75 95 69 106 107 112 57 64 56 54 74 114 88
81 75 90 62 50 41 68 73 77

BEV-D16A 78
122 164 140 94 88 155 139 179 164 118 120 132 152 137 133 138 188 158 150 128
137 114 144 100 126 108 172 165 168 138 141 124 136 127 133 146 147 140 130 136

138 102 127 139 124 125 182 170 163 241 205 166 147 148 192 134 98 161 138 122
151 126 130 136 102 123 115 93 100 90 134 92 87 101 91 125 134 95

BEV-D16B 78
127 149 146 92 94 150 142 169 175 127 120 128 163 138 138 141 183 172 134 123
135 121 136 96 115 111 173 163 177 129 155 114 138 130 141 141 155 132 139 146
124 103 121 149 141 115 198 168 165 241 209 174 149 146 167 132 100 149 124 134
132 145 121 129 104 112 110 97 100 85 136 89 99 91 85 121 133 79

BEV-D17A 108
71 175 124 104 118 133 108 117 120 157 164 173 130 123 154 179 188 164 140 130
127 130 115 139 155 115 131 136 137 132 119 145 116 201 183 147 108 104 127 133
134 127 126 109 104 117 171 155 136 155 89 76 121 126 114 87 134 135 119 85
77 97 105 82 107 79 98 94 93 92 85 89 96 84 77 98 94 86 82 100
96 75 89 131 81 108 134 100 111 115 92 79 88 70 88 71 90 75 80 76
75 87 103 81 76 63 52 65

BEV-D17B 108
108 169 136 105 113 124 113 115 117 155 167 171 148 116 150 176 197 152 141 136
126 125 111 146 158 105 120 139 129 124 125 146 108 197 182 143 107 106 123 132
136 129 125 109 107 113 176 156 134 158 85 76 120 126 118 86 127 137 123 84
80 99 107 82 101 84 100 101 88 93 87 91 101 84 78 97 95 86 84 94
97 84 86 120 93 111 133 104 110 110 97 78 86 73 88 72 89 80 83 67
77 89 108 80 81 58 55 64

BEV-D18A 154
121 173 127 88 50 44 51 72 170 176 98 55 46 33 36 71 123 153 141 103
128 99 132 155 157 138 119 112 149 167 182 156 140 143 122 73 98 128 142 148
148 171 165 112 78 71 120 101 117 114 111 83 106 64 71 83 70 88 58 50
82 59 80 73 96 97 67 85 59 42 59 82 79 76 79 60 67 73 62 77
73 78 45 54 79 74 85 70 81 72 45 44 45 53 54 68 74 71 79 73
42 37 27 34 46 47 48 40 31 38 37 73 68 70 63 59 57 58 55 69
76 62 58 64 37 29 47 76 89 75 80 85 88 88 92 100 79 47 72 78
62 59 87 88 104 76 82 83 73 127 144 119 227 201

BEV-D18B 154
117 170 133 101 30 46 56 64 168 164 91 54 55 26 36 72 120 144 139 114
124 102 144 173 167 135 122 104 157 167 187 154 148 133 122 82 90 122 136 144
153 159 167 119 83 70 111 104 125 110 103 90 99 69 70 82 77 91 60 56
75 60 73 72 88 102 71 82 64 42 56 70 85 91 82 59 65 64 62 73
79 74 43 62 74 84 96 67 82 73 43 47 44 52 55 71 76 69 82 71
40 32 27 35 45 42 49 44 35 33 36 77 66 65 61 62 56 53 57 67
78 59 64 58 38 35 50 64 90 80 79 79 92 92 90 102 79 51 76 70
63 63 93 95 99 78 75 87 78 114 151 133 220 198

BEV-D19A 136
390 369 286 227 232 179 279 285 254 269 265 215 219 146 132 139 174 231 113 84
98 91 154 105 106 140 219 195 172 142 158 138 246 163 138 292 281 177 112 135
122 148 124 127 92 121 160 157 131 153 118 131 132 200 114 181 174 183 178 131
96 94 69 80 50 91 71 113 83 93 98 97 102 91 95 98 83 81 80 83
109 125 96 103 75 60 72 96 83 81 65 61 55 93 87 86 79 73 68 70
78 82 88 96 97 108 96 78 84 67 59 65 53 70 70 65 114 83 63 59
73 84 82 53 76 66 69 82 66 68 75 53 49 41 57 65

BEV-D19B 136
356 402 253 229 246 193 264 275 252 278 258 226 219 144 133 136 175 256 114 105
111 83 154 102 114 146 221 201 162 127 147 161 237 164 134 291 283 180 108 135
122 149 126 135 91 122 155 163 131 148 156 158 138 202 105 183 190 165 187 129
99 92 65 85 58 78 78 106 91 82 112 94 90 98 94 109 87 84 80 89
106 109 86 109 72 61 69 93 84 77 65 68 51 90 85 86 73 72 76 67
77 85 83 90 105 102 96 74 88 70 53 71 61 63 72 65 115 86 67 59
63 98 84 47 76 71 66 78 76 70 68 60 47 48 58 60

BEV-D20A 141
332 259 242 258 188 188 178 121 174 181 170 197 224 210 228 229 171 189 169 133
145 98 118 125 96 84 87 153 197 178 165 173 123 97 114 114 147 146 166 207
191 170 129 147 134 114 177 214 171 215 182 137 165 170 153 254 241 228 245 245
176 108 178 201 168 251 164 173 214 207 172 165 182 256 299 209 129 180 259 182
167 182 180 106 150 187 137 102 133 140 158 66 52 55 55 38 52 61 47 68
48 53 80 61 36 32 31 59 82 94 118 97 69 78 44 39 37 37 49 34
40 34 42 38 40 44 59 38 47 33 37 38 30 43 47 59 52 56 59 60
60

BEV-D20B 141
335 253 249 264 179 189 175 122 174 178 166 176 226 212 224 227 172 191 188 116
145 100 121 121 86 93 78 155 199 174 168 176 121 100 103 126 144 146 164 209
190 173 133 148 127 112 182 216 172 213 185 141 158 174 152 251 246 226 245 243
181 110 172 202 173 240 169 172 211 206 169 166 181 257 306 210 125 182 254 184
162 183 180 108 146 192 136 108 132 139 156 67 58 49 49 41 49 63 50 64
49 55 80 62 34 29 27 61 79 94 117 98 60 98 50 40 26 36 50 39
31 32 52 36 38 42 62 45 37 33 36 42 29 42 45 53 64 53 61 59
53

BEV-D21A 66
295 291 268 251 358 261 222 295 335 287 310 317 328 251 162 179 133 213 176 123
124 114 95 63 100 117 194 242 284 221 393 124 108 84 88 80 91 96 76 48
86 85 78 90 85 122 177 150 196 268 233 264 203 207 291 155 159 84 115 92
28 31 30 30 35 44

BEV-D21B 66
273 284 276 250 362 260 219 296 336 293 307 319 328 246 162 177 140 195 178 121
133 118 92 64 103 114 196 232 287 232 387 122 107 83 86 80 92 95 77 52
81 85 77 92 83 124 176 154 204 259 246 263 192 207 269 157 159 82 116 95
31 29 29 30 37 45

BEV-D22A 63
155 163 250 203 175 213 215 162 157 167 211 206 382 329 276 186 237 192 128 168
126 164 187 148 190 124 225 143 158 144 121 93 110 117 82 62 70 78 98 128
78 46 78 98 83 61 51 113 82 119 85 73 89 75 73 93 96 114 151 199
223 191 224

BEV-D22B 63
157 173 268 218 202 238 224 175 168 181 200 221 407 354 371 178 243 169 137 169
170 151 188 141 213 128 216 148 149 150 116 95 100 120 74 61 68 81 85 123
70 50 74 90 77 58 46 91 70 100 92 70 76 73 70 92 101 109 132 169
205 176 197

BEV-D23A 86
343 207 296 159 114 98 89 118 244 218 128 131 69 100 88 87 108 81 193 57
67 115 68 106 119 128 147 111 198 137 113 119 191 102 184 93 61 114 174 100
92 116 211 182 147 139 127 181 107 120 156 179 177 187 233 277 209 206 153 148
150 110 130 254 238 254 250 227 163 182 210 255 180 206 279 302 219 170 155 107
193 205 154 127 156 108

BEV-D23B 86
321 212 277 155 118 89 86 119 251 217 145 120 81 88 93 86 117 82 172 69
59 115 63 104 121 120 143 110 196 125 141 136 201 112 167 89 72 105 168 100
91 127 209 172 152 154 118 188 103 126 150 180 173 191 233 248 210 222 152 150
157 114 129 248 237 266 244 229 162 180 191 254 177 214 273 301 227 170 157 107
196 206 139 132 156 110

BEV-D24A 75
506 263 593 543 667 687 395 331 342 413 389 539 339 217 139 181 167 134 91 176
144 97 119 154 196 134 75 97 148 130 212 163 172 174 152 97 80 50 93 155
140 115 111 122 103 89 170 141 123 42 34 75 114 147 192 239 128 73 58 75
59 93 125 102 109 94 120 158 173 155 103 125 108 100 156

BEV-D24B 75
504 249 607 535 642 693 462 320 341 383 378 548 364 195 143 160 163 124 99 166
153 78 130 155 200 124 70 84 137 141 213 174 177 167 156 95 82 52 76 160
139 111 109 125 89 99 172 133 108 39 38 75 114 148 193 244 123 73 56 69
61 90 126 106 109 94 114 162 169 147 113 115 100 93 164

BEV-D25A 102
335 185 139 217 235 307 239 273 255 288 278 341 361 332 336 196 204 219 217 242
328 310 252 247 248 210 223 353 277 254 239 219 177 202 222 187 197 195 180 198
117 124 263 306 280 247 221 247 197 203 217 314 303 295 253 261 324 239 235 275
330 228 142 198 202 233 250 186 156 167 118 182 135 111 126 114 152 192 145 246
219 138 123 148 168 162 112 111 150 179 109 101 98 84 117 147 163 160 149 208
124 138

BEV-D25B 102
334 181 139 216 250 299 237 270 254 302 266 341 369 333 344 203 206 229 214 228
343 312 261 239 241 212 232 346 275 253 237 223 179 197 225 181 195 200 182 199
128 137 269 308 278 235 212 240 195 206 221 321 301 305 245 268 318 234 232 291
326 218 139 203 198 235 249 186 161 157 120 186 131 115 125 113 148 196 153 235
221 143 121 149 166 164 110 110 146 185 106 104 108 90 113 146 158 165 155 210
121 137

BEV-D26A 83
120 149 102 90 89 104 150 186 142 74 150 239 267 221 101 86 105 53 102 195
114 186 123 90 97 154 195 164 218 106 270 190 351 265 367 340 482 246 313 182
235 276 364 278 242 287 278 179 205 82 166 205 203 302 191 128 163 118 224 199
147 124 145 138 117 80 143 168 231 138 220 91 222 214 214 225 278 216 140 113
199 203 191

BEV-D26B 83
122 147 111 79 84 100 151 187 140 71 153 238 277 220 101 86 105 51 104 195
114 187 122 89 94 155 196 161 226 102 266 194 348 266 387 332 487 256 321 171

225 274 360 274 247 287 277 177 201 83 160 207 194 317 191 129 174 125 228 194
147 136 145 140 111 83 144 159 235 145 219 97 222 209 218 223 275 219 147 114
195 200 192

BEV-D28A 50
282 386 438 501 386 417 362 354 399 345 352 348 366 356 350 248 271 323 347 496
511 318 365 360 337 314 260 195 181 261 252 219 177 158 234 260 237 277 241 299
232 218 189 207 236 207 222 193 286 209

BEV-D28B 50
276 405 438 487 387 407 370 360 416 356 350 352 356 361 350 248 272 323 348 496
513 318 364 360 351 310 258 193 187 256 247 211 183 162 236 253 232 274 274 298
227 214 192 214 246 221 212 196 276 184

BEV-D29A 52
170 285 413 420 650 595 673 747 610 658 604 655 580 627 500 488 543 524 608 396
310 332 354 235 247 177 249 255 342 343 258 254 277 125 128 115 148 137 123 90
84 94 85 106 59 67 104 89 82 116 94 115

BEV-D29B 52
194 274 402 405 655 603 696 701 604 666 591 644 571 626 502 496 551 513 615 422
328 335 336 238 233 169 260 244 350 353 257 248 260 125 132 115 148 138 128 86
78 91 96 102 66 59 110 89 79 124 86 119

BEV-D30A 58
357 399 453 386 316 320 286 223 144 287 321 378 371 286 134 159 268 241 238 191
170 124 230 153 169 66 63 128 143 212 139 177 187 152 102 61 93 118 130 106
86 102 96 107 74 92 71 64 56 92 57 49 63 64 94 54 57 44

BEV-D30B 58
361 393 439 381 311 320 283 223 144 286 315 383 404 274 138 163 262 244 232 196
165 123 222 153 172 63 64 117 132 216 138 178 184 143 107 55 98 124 122 113
80 102 92 114 61 76 77 70 67 88 60 44 65 69 92 59 56 43

BEV-D34A 85
230 264 252 162 237 162 160 234 331 233 203 214 205 222 209 193 276 216 175 203
212 142 148 149 134 138 128 125 118 104 86 134 123 97 141 155 129 141 127 109
129 142 159 147 159 125 123 146 117 109 50 24 28 39 40 34 36 39 41 40
50 53 50 47 64 74 57 57 61 59 37 47 52 51 58 54 40 51 54 50
42 50 48 48 48

BEV-D34B 85
221 264 252 162 240 161 149 219 327 227 215 209 210 230 201 208 281 218 181 171
218 160 130 145 139 130 128 110 116 97 94 134 135 99 141 154 132 136 114 107
126 145 162 145 161 122 120 146 119 109 49 33 26 39 34 34 37 42 36 39
51 56 45 46 68 71 54 58 64 58 39 44 52 50 58 49 43 51 52 52
43 53 41 46 49

BEV-D35A 67
218 42 129 161 154 119 259 504 349 331 369 372 306 188 196 353 336 349 257 237
256 298 203 110 135 263 154 286 321 341 236 102 159 219 227 207 253 244 149 87
147 144 125 142 154 86 100 176 115 130 96 83 45 40 46 70 95 76 69 89
32 33 30 49 44 19 21

BEV-D35B 67
234 91 126 189 214 166 248 510 348 333 373 354 303 185 219 334 330 358 256 238
250 298 201 115 139 265 162 287 350 324 234 102 166 217 208 216 252 232 152 87
145 144 129 137 151 75 103 175 119 121 99 75 51 41 50 67 98 88 68 71
41 32 29 58 38 29 21

BEV-D36A 121
167 204 243 157 149 164 176 232 255 256 118 175 336 196 198 337 300 260 124 117
244 280 178 146 283 154 244 196 251 170 182 187 196 244 254 208 148 282 253 168
236 229 263 153 170 117 124 149 176 247 168 181 167 236 169 239 181 253 246 168
193 161 232 201 234 168 135 110 208 152 99 142 98 137 118 63 91 116 113 126
145 90 100 91 97 82 76 149 112 73 62 81 165 127 153 120 141 118 112 66
82 128 124 102 120 115 74 81 97 81 105 78 72 64 57 88 58 43 72 97
98

BEV-D36B 121
173 197 247 168 150 160 180 237 264 260 122 150 328 222 192 357 304 285 125 128
262 282 205 127 298 160 242 200 262 186 192 207 187 242 245 221 151 263 265 168
242 220 252 160 172 118 133 143 177 252 171 162 175 237 169 234 178 243 263 165
211 168 228 206 235 160 135 123 206 152 93 141 107 128 120 78 78 102 129 132
117 120 90 97 100 72 79 140 117 69 63 86 166 130 152 127 147 115 112 85
79 138 131 99 119 118 85 76 91 91 99 83 69 68 62 87 56 56 57 98
97

BEV-D39A 79
153 286 156 159 121 117 145 217 292 224 189 179 219 179 159 222 197 156 211 136
126 121 164 154 143 122 137 143 155 85 143 127 133 94 111 145 96 93 147 168
130 125 129 73 57 46 47 64 78 128 109 86 120 67 67 37 32 43 91 62
56 39 62 79 56 73 67 61 49 41 36 43 78 80 80 56 38 49 58

BEV-D39B 79
172 281 152 142 116 126 146 204 271 206 165 163 205 171 169 203 184 146 212 141
127 113 166 146 147 123 138 140 157 81 148 122 136 88 116 142 95 94 144 173
129 123 130 71 54 51 46 62 80 128 107 90 117 73 59 37 39 40 83 69
50 39 68 80 53 72 69 70 37 37 39 49 83 71 78 49 41 57 69

BEV-D40A 72
208 297 266 255 289 149 197 123 177 149 113 110 71 63 73 91 127 154 245 191
140 254 168 145 174 171 161 171 173 188 187 148 207 178 278 272 269 280 246 206
274 257 201 150 172 230 252 239 209 226 144 128 115 192 164 163 224 125 170 231
242 271 150 127 186 203 151 244 198 186 144 139

BEV-D40B 72
218 298 266 262 288 143 217 127 171 148 97 105 65 62 84 79 129 146 218 203
148 242 159 160 179 175 145 165 174 188 198 146 206 173 267 264 263 290 242 208
272 259 198 156 175 237 250 233 219 218 151 126 115 192 163 165 230 117 177 231
247 264 151 128 185 202 159 248 212 177 142 133

BEV-D41A 107
202 137 111 130 109 93 94 97 90 109 146 180 116 143 151 85 85 125 155 142
134 111 90 144 82 89 100 109 89 110 134 103 84 86 105 105 89 83 69 78
84 63 73 61 56 47 57 66 56 63 78 100 120 69 71 81 96 134 79 87

70 83 72 78 94 99 90 69 66 72 68 54 50 42 70 65 83 48 57 49
52 84 109 109 106 78 97 78 96 89 116 103 150 149 110 103 101 102 181 160
141 170 126 149 117 84 104

BEV-D41B 53
73 92 72 73 64 72 84 46 67 65 76 67 54 58 61 40 57 40 71 75
81 43 38 39 56 82 119 143 134 118 104 72 110 114 183 150 230 187 153 109
120 117 219 211 157 265 163 177 151 119 152 271 311

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Nottingham Tree-ring Dating Laboratory's Monograph, An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings (Laxton and Litton 1988) and Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. Inspecting the Building and Sampling the Timbers.

Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample in situ timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and

Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical

2. Measuring Ring Widths.

Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. Cross-Matching and Dating the Samples.

Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. Estimating the Felling Date.

As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/ sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. Estimating the Date of Construction.

There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences

Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices.

Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

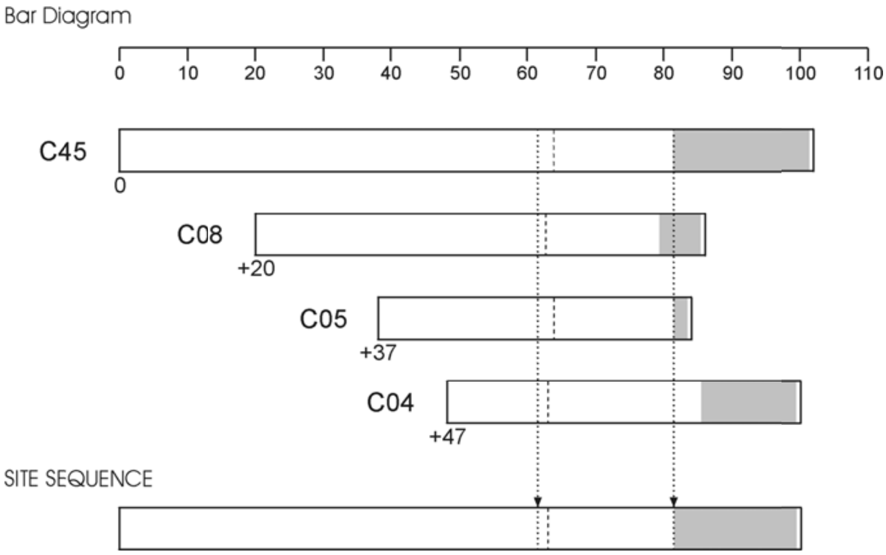


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum t-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

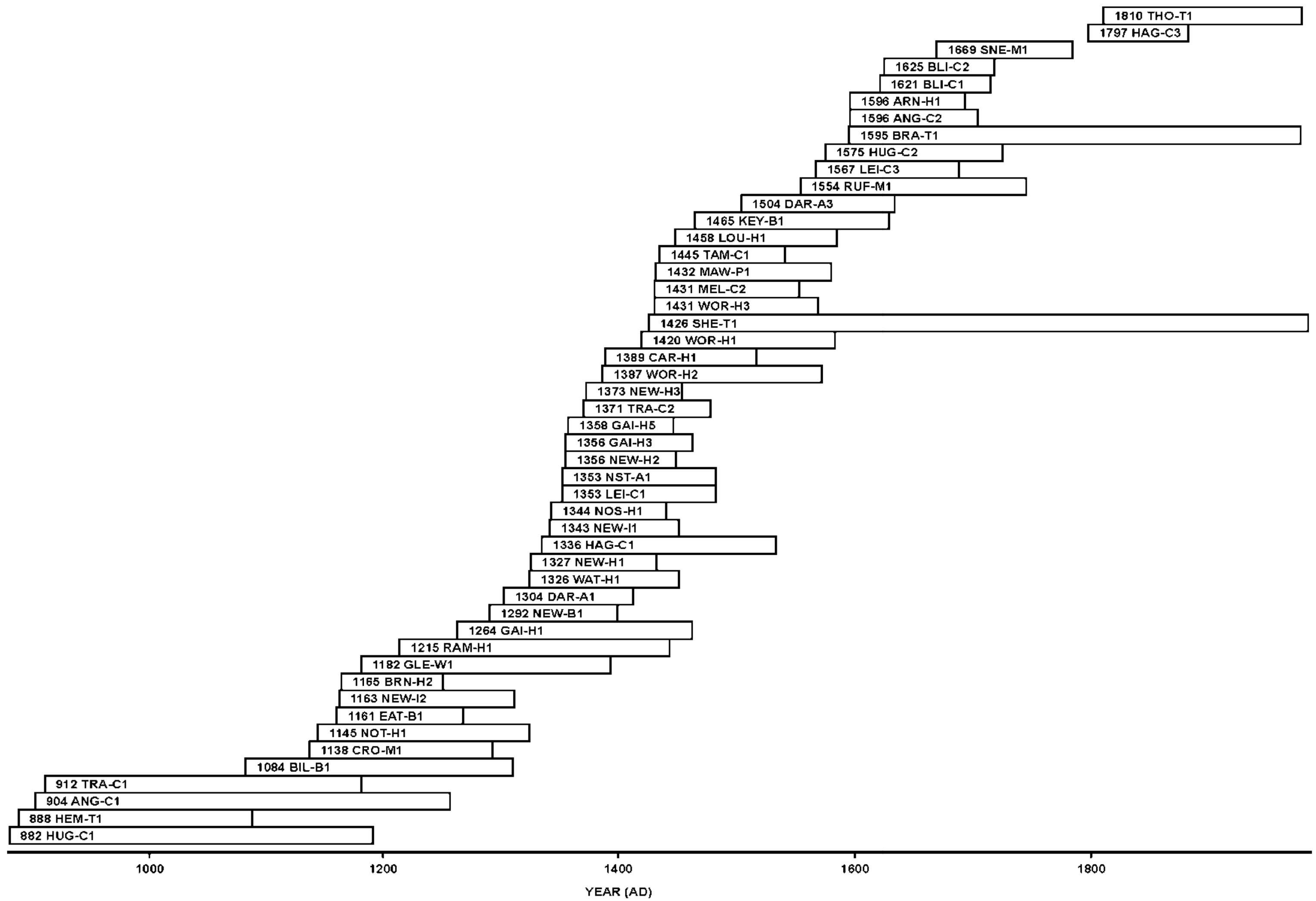
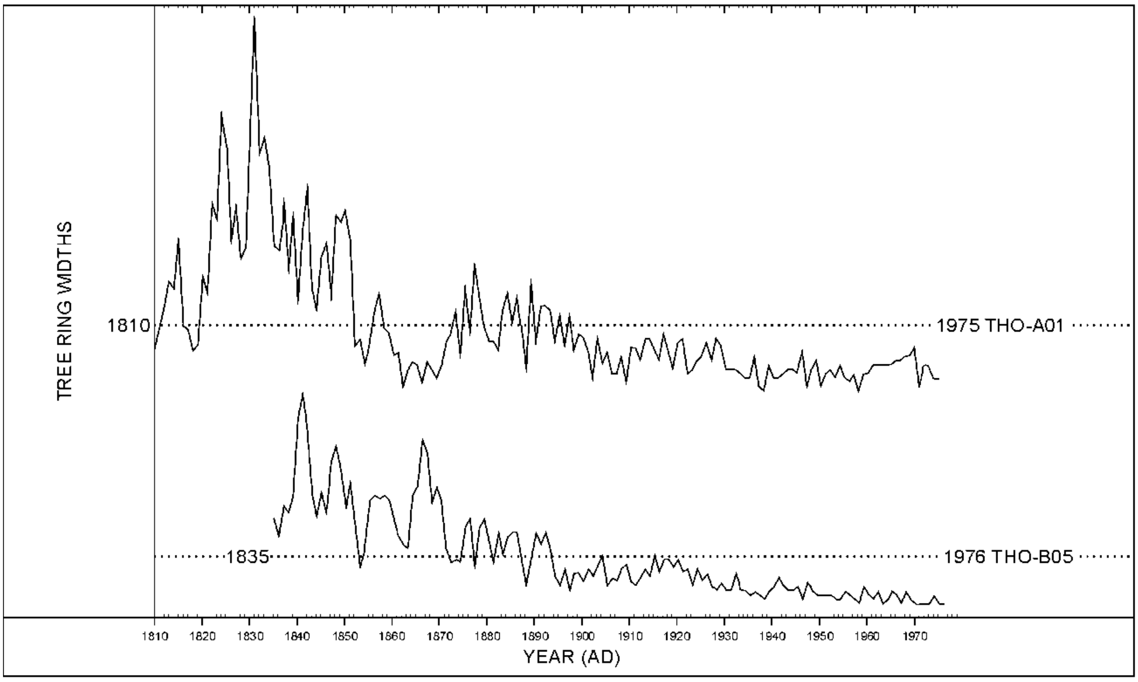


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

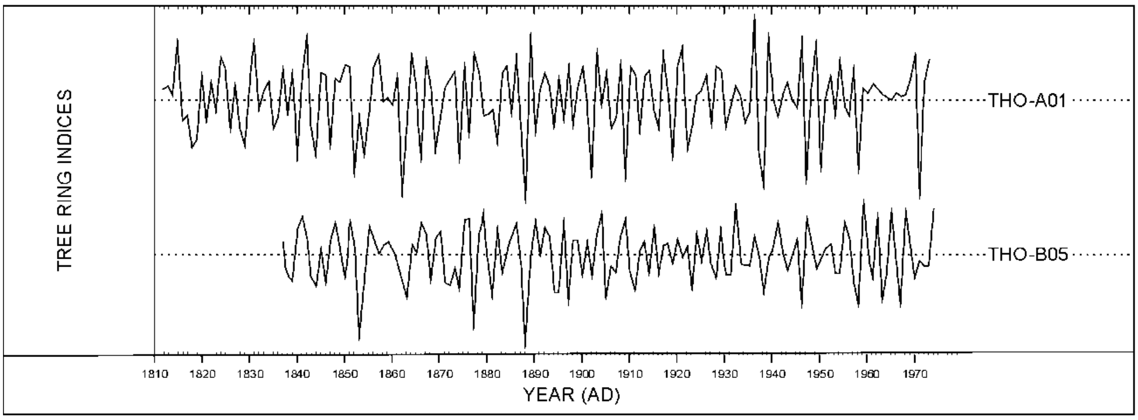


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known
Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences.

Figure A7 (b): The Baillie-Pilcher indices of the above widths
The growth trends have been removed completely.

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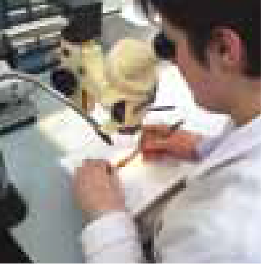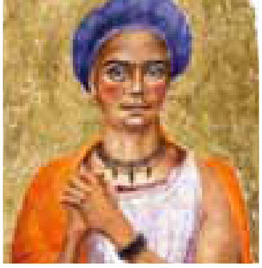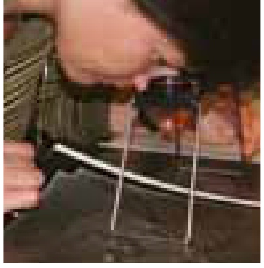

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